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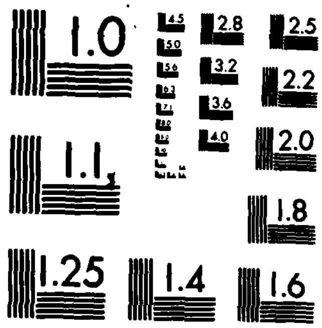

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LIGHTNING TESTS ON THE WC-130 RESEARCH AIRCRAFT

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December 1982

FINAL REPORT FOR PERIOD OCTOBER 1981-SEPTEMBER 1982

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FLIGHT DYNAMICS LABORATORY
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Lightning simulation ground tests were conducted on a WC-130 aircraft which had previously been used by the Air Force in a lightning characterization program to investigate the electromagnetic field environment experienced by aircraft near active thunderstorms. Two types of lightning simulation tests were conducted. One technique used a Marx generator connected directly to the aircraft as the system stimulus. The second technique used the generator to abruptly charge a long horizontal wire which radiates the isolated aircraft with an electromagnetic pulse. Induced voltages on two interior wire pair circuits were measured.

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SECTION I
INTRODUCTION

The Electromagnetic Hazards Group of the Air Force Wright Aeronautical Laboratories has completed a three-year lightning characterization program. A National Oceanic and Atmospheric Administration (NOAA) WC-130 aircraft was instrumented with wide-band electromagnetic field sensors and two simple interior wire circuits and flown in close proximity to active thunderstorms to record the characteristics of the electromagnetic fields and induced transients in the aircraft environment.

The flight program progressed from a rather simple instrumentation system the first year[1] to an expanded memory ten-channel digital and multichannel analog system the second year, to the same airborne instrumentation with correlation to a ground station network the third year.[2] A very large amount of data characterizing, nearby lightning activity and two direct strikes has been gathered in the program and is currently being analyzed by the Air Force. This large data base should greatly expand the lightning community's understanding of the interaction of an aircraft in flight near a thunderstorm environment.

The purpose of the ground test program described in this report was to measure the response of the interior wire circuits and the aircraft's electromagnetic sensors to a controlled ground test environment that simulates the electromagnetic effects of lightning. The specific objective of the program was to study the response of the interior wires to both the current pulse and the shock-excitation test techniques. The tests were performed by the lightning laboratory of McDonnell Aircraft Company (MCAIR) during the week of 16 November 1981. This one-week test period was after the third year of the flight program and before the WC-130 was decommissioned from use by NOAA.

SECTION II
BACKGROUND

As the understanding of the natural lightning environment improves, it is necessary that advanced ground test techniques be developed to correctly assess and predict the electrical transients produced in aircraft wiring by lightning. Recent advances in aircraft technology have tended to raise the susceptibility of the critical avionics systems to damage or upset by lightning. Advanced graphite epoxy composites, with their much lower electrical conductivities, are being used to replace metallic skin and substructure components. State-of-the-art microelectronics are being used to computerize flight command and control functions. These advances make it increasingly important that the lightning qualification and induced voltage test techniques simulate all the electromagnetic coupling mechanisms and parameters present in the lightning environment. Continued lightning test technique development must ensure that possible damage or upset due to lightning is detected on the ground before catastrophies occur in flight.

In an attempt to better simulate the natural lightning environment, MCAIR has developed the shock-excitation test technique under an independent research and development (IRAD) program. The MCAIR test approach uses a test setup that differs from the current pulse technique in a few key respects. Most importantly, the aircraft is charged to a high voltage before the high-current discharge occurs. A high-voltage generator is used to arc over both input and output spark gaps, so that both voltage and current stimuli are applied to the test article. This technique allows the simulation of the three phases of a lightning strike: (1) the fast electric field changes produced by nearby flashes (generator is triggered), (2) the stepped-leader attachment to the aircraft (spark gap between generator and test article breaks down), and (3) the current return stroke (output spark gap breaks down to form a continuous current path). During the second phase, the test article is elevated to a high potential with respect to the nearby return conductor. The large voltage difference produces high electric fields typical of the strike environment. When the output spark gap breaks down, the electric fields are shorted. This causes a rapid voltage variation and the initiation of the discharge current pulse. The fast changes in the test article voltage and current excite both capacitively and inductively coupled circuits.

Although the shock-excitation was initially developed using a long aluminum cylinder in the MCAIR lightning IRAD program, the test technique has now been widely applied to many test articles that include the NASA space shuttle orbiter (OV101),[3] the NASA F-106B lightning research aircraft,[4] and the composite wing of AV-8B Harrier.[5] A key element in the shock-excitation test technique development was the test program done to compare the induced voltage responses of the current pulse and shock-excitation test techniques. This work was performed under contract to Wright Aeronautical Laboratories and included tasks to experimentally compare the induced voltage responses for the two techniques on first the aluminum cylinder and then the YF-16 prototype fighter aircraft.[6] The work described in this report is a continuation of the Air Force contract to compare the two test techniques.

The WC-130 test program was designed to compare the two test techniques using the same generator and test equipment that were used in the YF-16 and cylinder tests. The comparison of the induced voltage responses was to be made for several different current and voltage levels while monitoring both the interior wire circuits and the aircraft's electromagnetic sensors. The ultimate goal of the project was to provide the Air Force with the aircraft's wire and sensor responses for both test techniques so that these could be compared to the responses observed in flight.

Due to several program difficulties, the tests were not able to be conducted as initially designed and, therefore, did not adequately compare the two test techniques. Data from the interior wire circuits and some sensors were gathered instead for both a direct current drive and radiated field test conditions, as are described in Sections III and V.

Two principal problems limited the amount of useful data taken in these tests. Initially the test program was to be conducted at Wright-Patterson Air Force Base (WPAFB) where adequate test support and technical personnel were available. Due to flight limitations on the WC-130, the test location was changed to Homestead Air Force Base, in Homestead, Florida. There the tests were conducted on the flight ramp with minimal test equipment and logistics support.

The large wooden return conductor supports were provided by the Air Force and had to be built at WPAFB and transported to Florida. When installed around the aircraft, the supports were not large enough to provide adequate clearance of the return wires from the aircraft. When an output spark gap was included between the aircraft and the return conductors, random arcing occurred from the return wires close to the aircraft. The arcing did not allow much potential difference to be applied between the aircraft and the return system, and thus prevented the shock-excitation test method from being used in the test program.

The other problem was that the test setup was designed for nose-to-tail current flow, and the aircraft's fuselage sensors and instrumentation system were designed primarily to monitor the electromagnetic activity produced by nearby lightning discharges. The stronger electromagnetic fields produced by the direct attachment to the high-voltage generator caused all the fuselage sensors to saturate. Only wing sensors (left wing tip $\dot{D}$ and wing $\dot{J}$s) outside the coaxial current return system responded on-scale. To prevent the saturation, it was necessary to remove the current return conductors and to radiate the aircraft by firing the generator into a long horizontal wire. This radiated test method produced on-scale signal responses for the abrupt charging of the output line, but it had the disadvantage that the input radiated pulse was not well-characterized.

SECTION III
TEST SETUP

The aircraft was tested using two different test configurations. The first test setup was typical of that used in most full-scale aircraft lightning tests. The WC-130 and a "coaxial" current return system were connected directly to a high-voltage Marx generator. In this configuration, oscillatory (500 KHz) current pulses of approximately 6 KA were applied to aircraft. These currents enabled us to accurately map the fuselage skin current distribution, but they produced field and induced-voltage levels that in many cases exceeded the measurement range of the on-board data system. The fuselage sensors were primarily designed to measure the lower level nearby lightning activity experienced in the flight program, so a second test configuration was used to simulate a nearby field transition. The generator was moved away from the aircraft and was fired into a long horizontal wire which was open-circuited at the other end. This test configuration exposed the aircraft to a radiated pulse due to the abrupt charging of the long line.

This section first describes the MCAIR data and Marx generator systems used in these tests. Then the two test configurations are described.

1. Data System

The data acquisition system was located in a portable screen room and is shown schematically in Figure III-1. The main system components include fiber optic (F/O) data links, four transient recorders, and a controlling computer system. Four digital transient recorders (two Biomation 6500s, a Biomation 8100, and a Textronix 7612) were used throughout the test program. When coupled with their respective fiber optic data links, the transient recorders permitted the simultaneous measurement of up to five data channels on each test shot.

Fiber optic data links were used in all tests to transmit the desired electrical responses to the recording equipment located in the interference-free shielded enclosure. The WC-130 sensor outputs were first sent by the Air Force's fiber optic transmitters to the on-board control console where they were reconverted to their electrical equivalent by F/O receivers. During flight

(A fourth transient recorder and two additional fiber optic channels were used in the WC-130 tests at various times.)

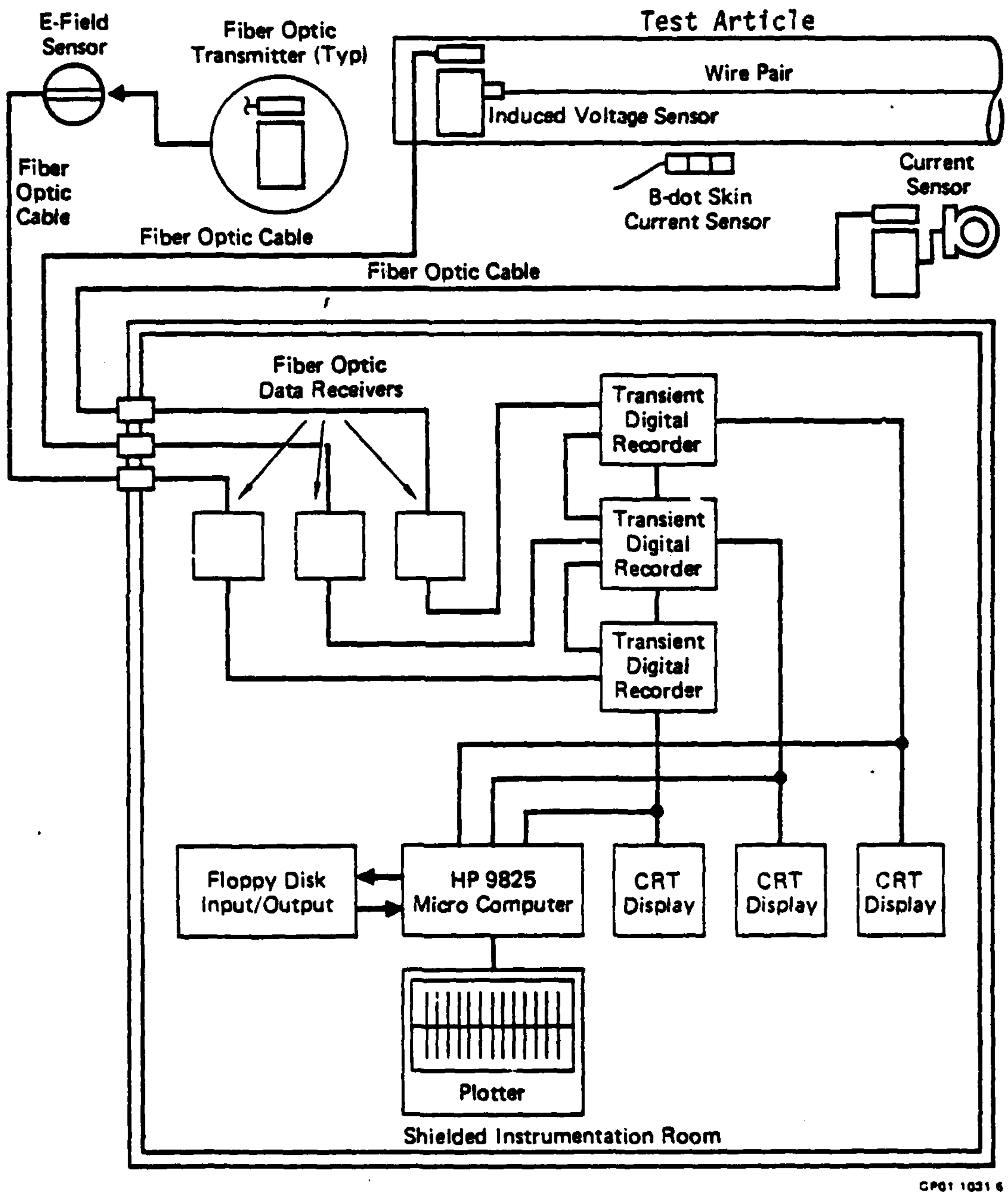

FIGURE III-1. MCAIR INSTRUMENTATION SYSTEM FOR THE WC-130 TESTS these electrical responses would have been processed by the Air Force's combined digital/analog recording system and ultimately stored on magnetic tape for later retrieval. However, in these lightning tests, the electrical responses were again converted to their optical equivalents and sent by a MCAIR F/O system to the shielded enclosure, located outside the aircraft. The induced voltage responses of the WC-130 interior wire circuits were produced at the on-board control console. The wires' responses were either: (1) measured directly by the MCAIR F/O data links or (2) processed by the Air Force's data channel (as in flight) and then transmitted by MCAIR F/O data link to the shielded enclosure.

The MCAIR fiber optic data links include a battery-powered transmitter, a receiver, and an interconnecting fiber optic cable. The fiber optic transmitter uses a high impedance differential amplifier to drive a current amplifier which in turn drives a light-emitting diode within its linear range. The output is a signal modulated light pulse which is transmitted by multistranded fiber optic cable. The transmitter has common mode rejection of -40 dB at 15 MHz and can produce variable voltage gains up to ≈150. The transmitter has a usable charge life of four hours. The fiber optic receiver reconverts the optical signal into its electrical equivalent. The main receiver components are the receiver diode, a video amplifier, and a current amplifier to drive the 50-ohm input impedance of the transient recorders. The transmitter/receiver pair have a bandwidth of at least 20 MHz.

Control, data recording, and data manipulation were handled by a Hewlett Packard 9825 microcomputer with additional plotter and floppy-disk capability. The extensive software system was structured so that one controlling program could be used to call any of 28 subroutines to perform the basic data recording, display, storage, and processing tasks. Memory space was held to a minimum by having only the controlling program and a binary FFT program in memory at any time. All data were stored on cassette magnetic tapes to provide a permanent test record.

2. Generator System

The pulse generator system used for these tests was designed and built at MCAIR. The system includes a high-voltage Marx generator, a power supply, and a charge/dump switch. The generator is modular so that stages can be added or removed as the test requires. Each stage contains a spark gap switch, charging resistors, and a 0.032 μF capacitor. Each stage can be charged up to 100 KV.

The charge/dump switch is air-operated and is designed to eliminate extraneous ground paths. Before the isolated generator is triggered, the charging power supply is completely switched out of the circuit to remove any connection to ground potential. To operate the system, the test operator actuates a spring-loaded air valve at the console, charges the generator to the required stage voltage, and then releases the air valve. A pneumatic actuator disconnects the charging supply's ground and the high-voltage charging lead, and a trigger signal is sent to the spark gaps. If the tower fails to discharge within a few milliseconds, the tower safety discharge will automatically activate. The entire system immediately returns to the safety discharge state if either air or electrical power is lost.

3. Current Test

The aircraft was positioned on dielectric pads so that the applied test current would be entirely contained within the aircraft/generator circuit. The pads were designed to isolate the aircraft to 500 kilovolts from the earth ground. Each dielectric pad was made of Lexan sheet material and was designed to support the weight of the aircraft. The high-voltage standoff capability was achieved by configuring the Lexan to preclude any direct punch-through to ground and also using an oil dielectric to eliminate surface flashover from the tire to the outer edge of the Lexan. Figure III-2 shows the details of the left main landing gear pad.

Figure III-3 shows the overall test setup. The aircraft was positioned inside a "coaxial" return system provided by the USAF. The return system consisted of 18 wires strung from the output at the tail to the low-voltage side of the generator located near the nose. Six wires were located above the fuselage, and four wires each were located on the sides and beneath the fuselage. The wires were supported by four wooden stands to make the wires approximately one half meter from the fuselage at the stands; however, the wires sagged between the stands so that in some areas they were nearly touching the fuselage.

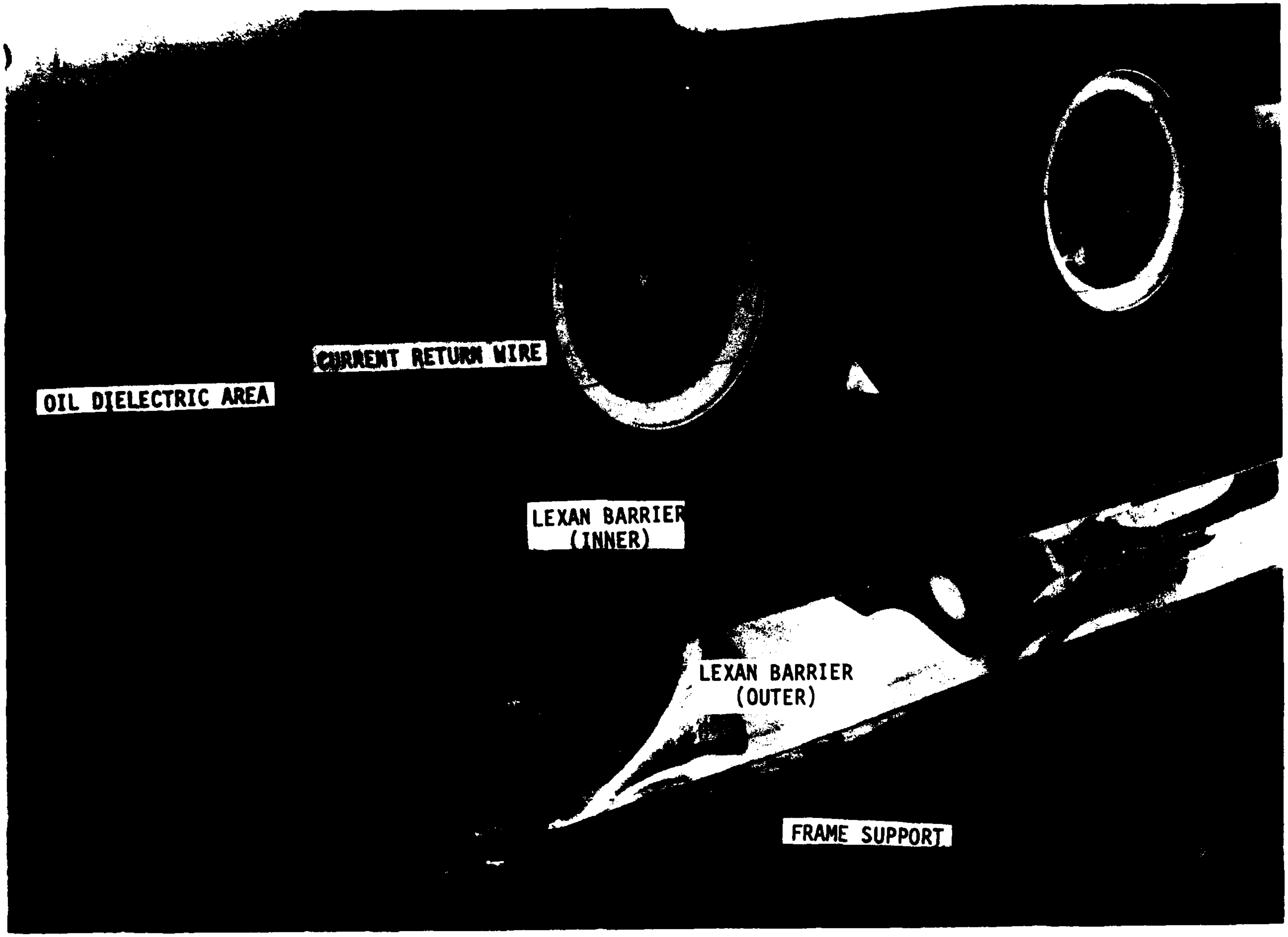

FIGURE III-2. DIELECTRIC ISOLATION PAD FOR THE LEFT MAIN LANDING GEAR

FIGURE III-3. OVERALL WC-130 TEST SETUP

Figure III-4 shows a closer view of the generator area near the aircraft's nose. The high-voltage generator was mounted horizontally so that it could be contained within the return conductors. The generator was located about 10 feet from the radome, and the current output wire was routed to the static grounding connection about 4 feet aft of the radome edge. The current return wires were routed back to a single support post, and then connected to the low-voltage side of the generator.

4. Radiated Test

For the radiated tests, all of the current return wires were removed from the aircraft, and the generator was moved to a position beyond the wing tip but even with the nose. The generator's output was connected to a long wire that was three meters above the ground and oriented parallel to the longitudinal axis of the aircraft. The wire was left open ended at the far end so that the fast rise voltage pulse from the generator was directed into the wire as a high impedance radiator. The opposite side of the high-voltage generator was connected to earth ground. Figure III-5 shows the generator setup with the wire radiating element.

This same type of electrical setup was used to radiate to the aircraft in an orthogonal axis. The wire was placed near the tail of the aircraft and was parallel to the wing axis. All other test conditions remained the same. Figure III-6 shows the tail radiation test setup.

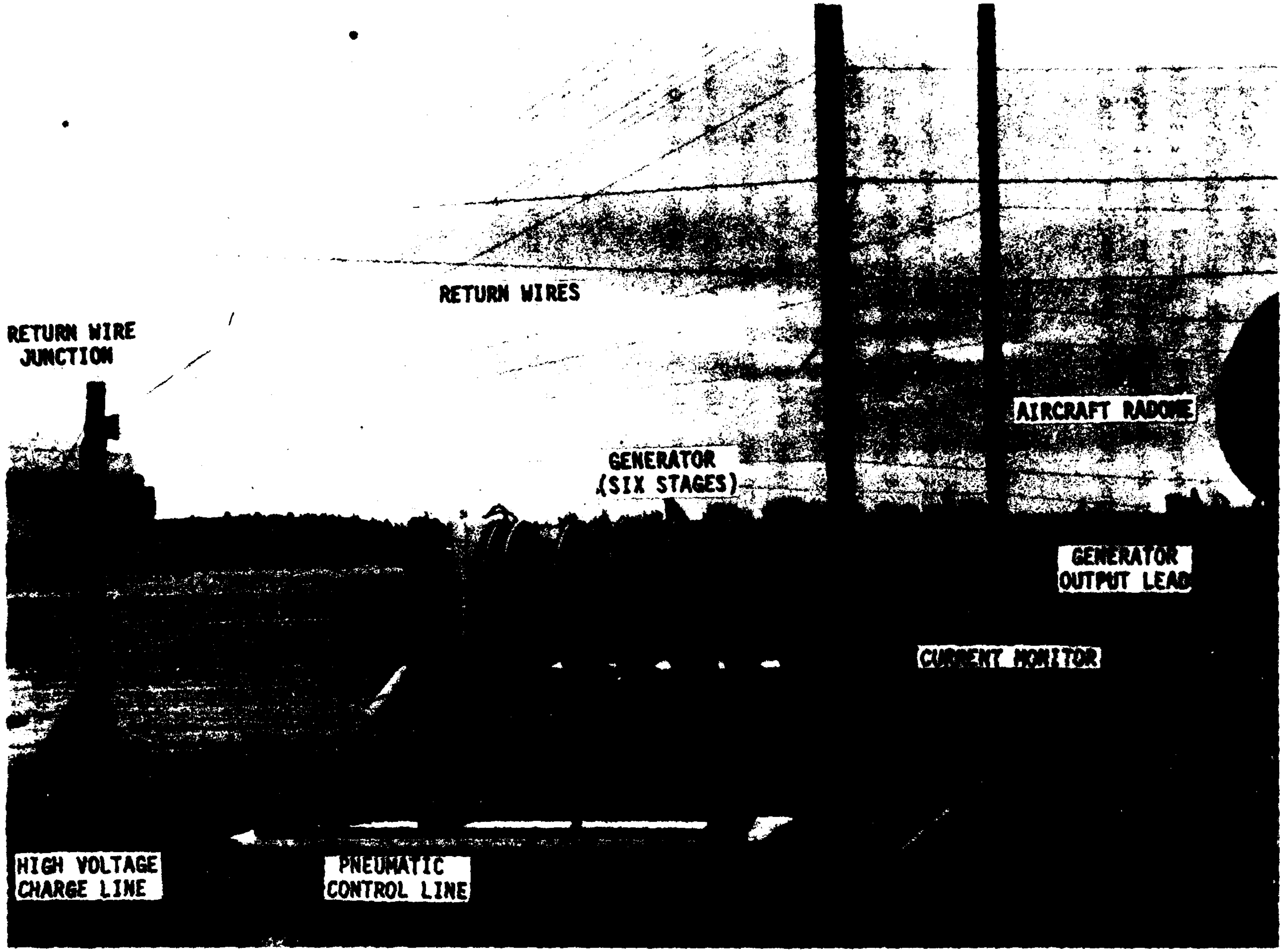

FIGURE III-4. GENERATOR AND NOSE AREA

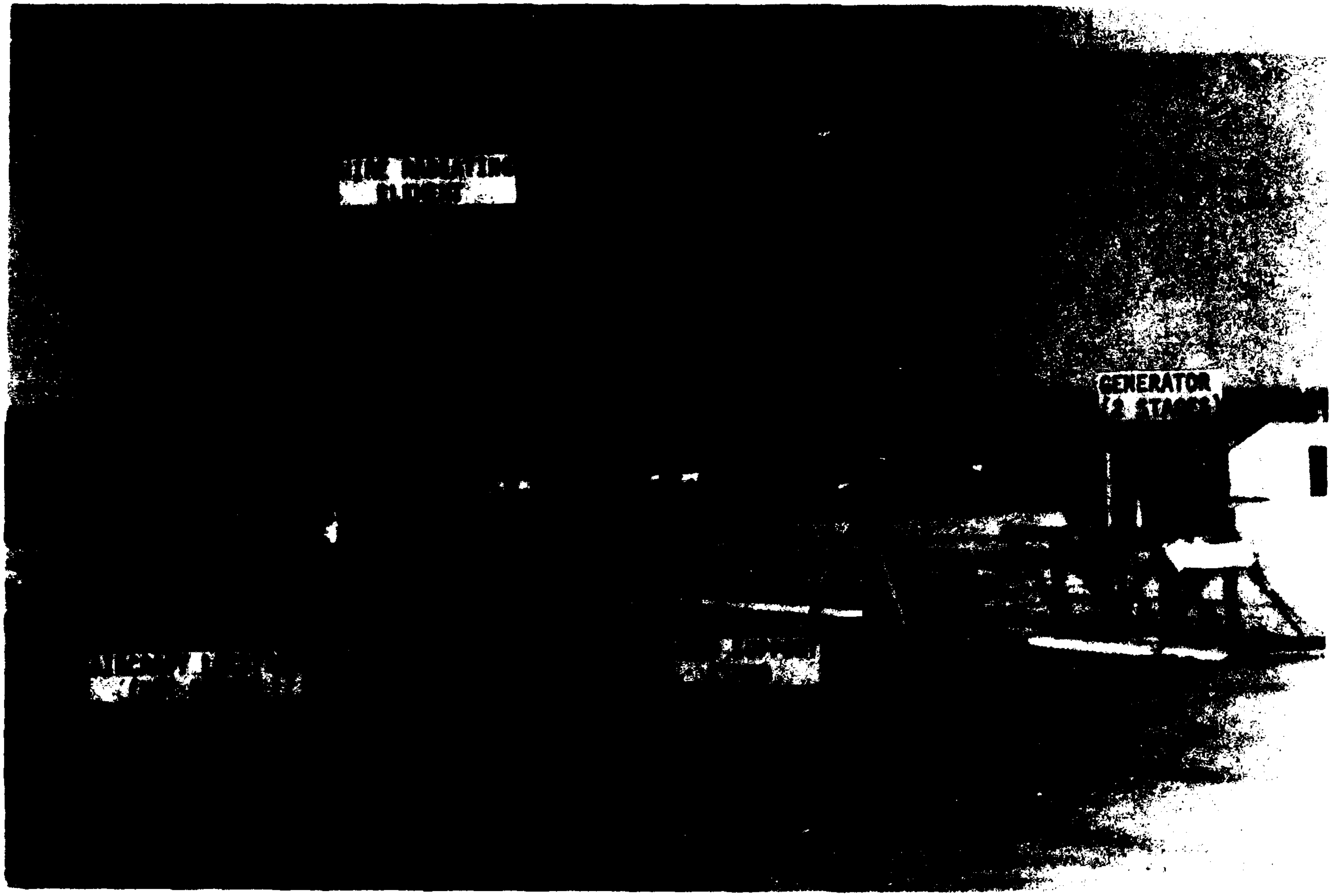

FIGURE III-5. RADIATED TEST SETUP

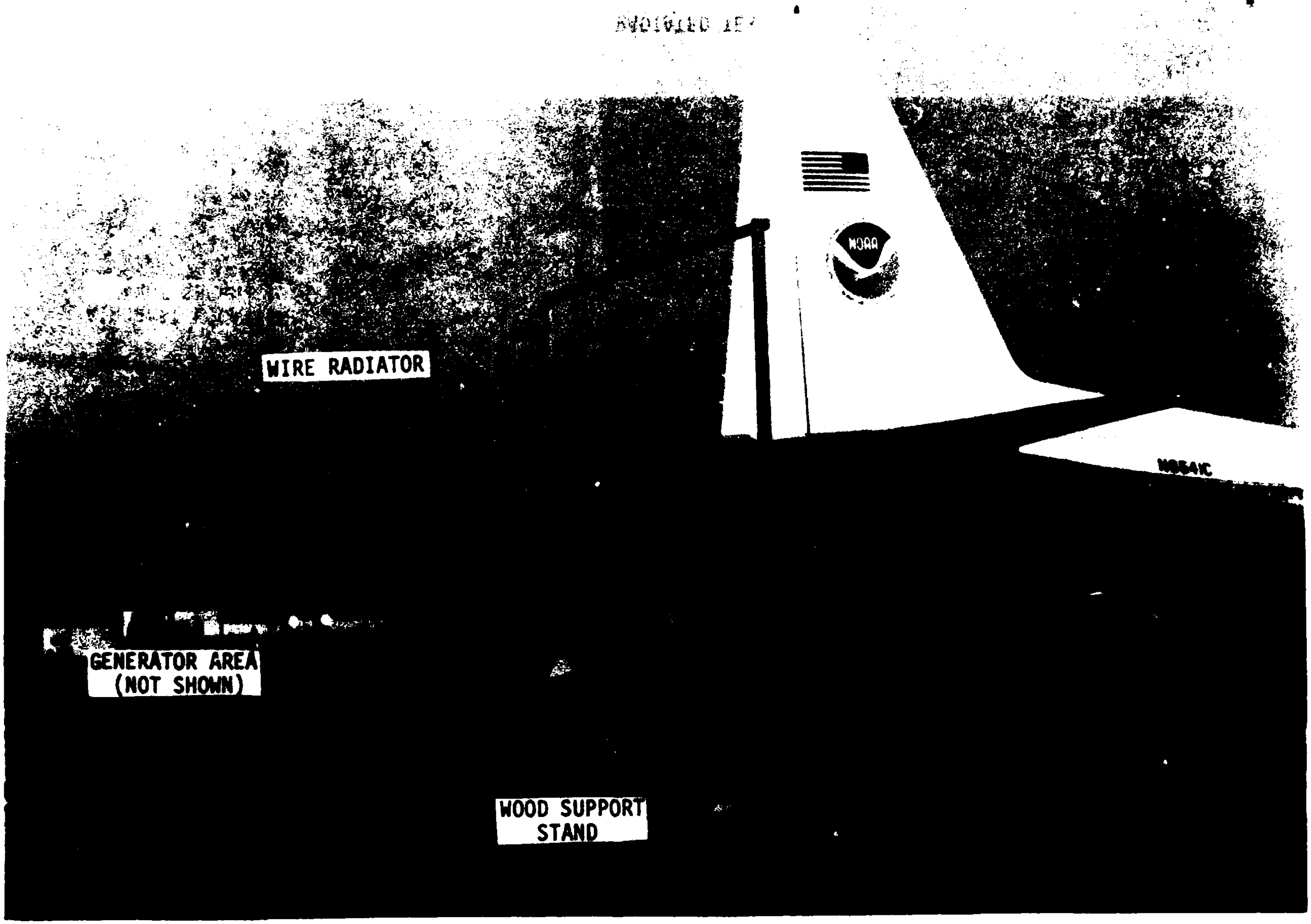

FIGURE III-6. TAIL RADIATED TEST SETUP

SECTION IV
AIRCRAFT CONFIGURATION

The WC-130 is the standard turboprop aircraft that has been used by NOAA during its mission to chart the characteristics of severe weather in the southeastern part of the United States. This particular aircraft had been adapted to monitor thunderstorm electromagnetic activity by mounting electromagnetic sensors at several locations on the airframe. These sensors detect electromagnetic field and current changes. The outputs of the sensors are then transmitted by fiber optic data links to a central monitoring station where the data are recorded on magnetic tape for later analysis.

Eleven sensors were located at points on the external surface of the aircraft. The type, location, and use of these sensors is listed in Table IV-1, and their locations are shown schematically in Figure IV-1. Figures IV-2 and IV-3 are photographs showing several of the sensor types mounted on the aircraft.

In addition to the 11 sensors, two wire pair circuits had been incorporated in the aircraft prior to the flight program to monitor the induced voltage responses caused by nearby lightning activity. One wire pair consisted of two single 18-gauge wires that were run from the fiber optic receiver console to the left wing tip. These wires were positioned randomly in an existing airframe wire bundle. The total length of the wing wire was approximately 66 feet, and the wires were open-circuited at the wing tip for these tests.

The second wire pair was a 300-ohm twin-lead cable that was routed from the fiber optic receiver console to the fuselage center cable run. This wire went aft to a point near the rear side doors and then was routed to the right side of the fuselage and across the side view ports. From the side ports, the wire was routed across the rear top inside fuselage to the left side and down to a point about 3 feet from the floor. At this location, the wire was routed into a circuit switch to permit the selection of either an open or short circuit condition. The total wire length of 56 feet was all contained with a 22-foot section of the aft fuselage.

TABLE IV-1. WC-130 LIGHTNING CHARACTERIZATION SENSORS

SENSOR	MODEL	TYPE	USE	LOCATION
1	EG&G CML-7(R)	$\dot{J}$	Wing Surface Current	Left Upper Wing
2	EG&G CML-7(R)	$\dot{J}$	Wing Surface Current	Left Lower Wing
3	EG&G CML-7(R)	$\dot{J}$	Wing Surface Current	Right Upper Wing
4	EG&G CML-7(R)	$\dot{J}$	Wing Surface Current	Right Lower Wing
5	EG&G FPD-2B(R)	$\dot{D}$	Wing Electric Field	Left Wing Tip
6	EG&G CML-S7A(R)	$\dot{J}$	Fuselage Surface Current	Rear Up. Fuselage
7	EG&G CML-S7A(A)	$\dot{B}$	Wing Axis H-Field	Fwd Up. Fuselage
8	EG&G CML-S7A(R)	$\dot{B}$	Fuselage Axis H-Field	Fwd Up. Fuselage
9	EG&G HSD-S1A(R)	$\dot{Q}_S$	Electric Field	Rear Up. Fuselage
10	EG&G FPD-2(A)	$\dot{D}$	Electric Field	Fwd Up. Fuselage
11	EG&G FPD-2(A)	$\dot{D}$	Electric Field	Rear Lwr Fuselage
-	Twisted Wire Pair	-	Induced Transients	Left Wing
-	300-Ohm Twin Lead	-	Induced Transients	Ctr of Fuselage

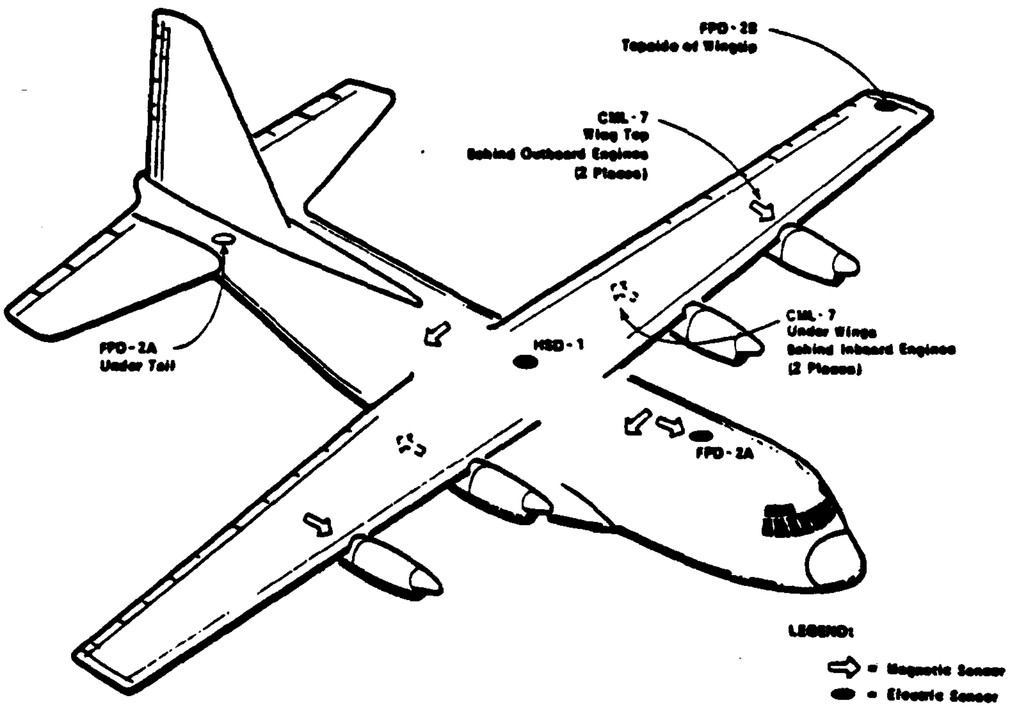

FIGURE IV-1. WC-130 SENSOR LOCATIONS

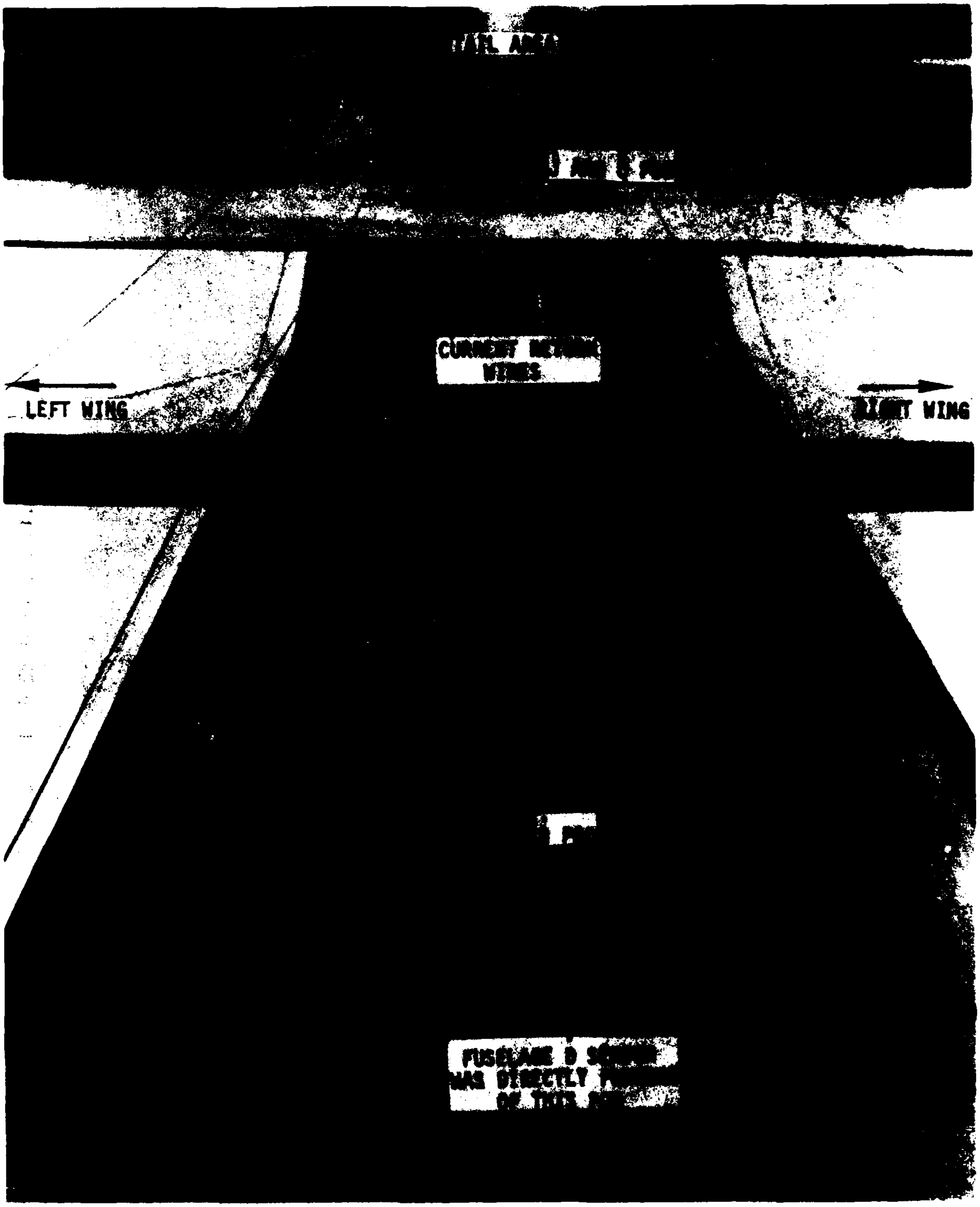

FIGURE IV-2. FUSELAGE SENSORS

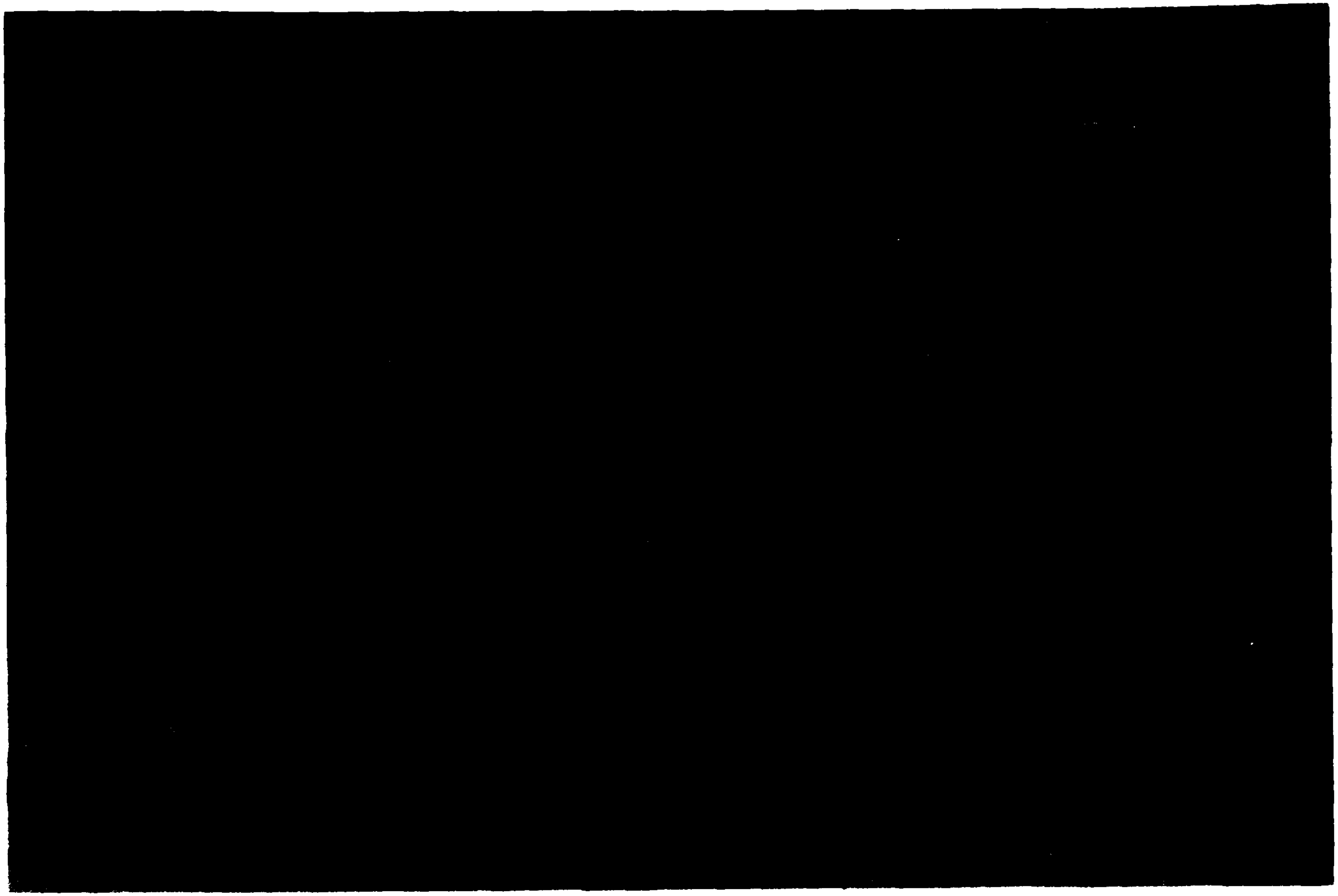

FIGURE IV-3. J-DOT SENSOR ON THE UPPER LEFT WING

Data from the EG&G sensors were monitored during the test by the USAF fiber optic receiver system that was mounted midwing in the aircraft. Each optical signal was received at a control fiber optic receiver console that was powered by a battery-operated 60-Hz generator set for these tests. This battery system permitted the data links to operate as they do in their normal airborne configuration without reference to ground-based power. The fiber optic receiver system consisted of the separate receiver channels that included the receiver diodes, log amplifiers, and filters. Table IV-2 shows the input/output relationship of each signal source and data channel output.

TABLE IV-2. RECORDED OUTPUT VOLTAGE (V_o) FOR THE DIFFERENT AIRCRAFT SENSORS

SENSOR TYPE	DERIVATIVE RESPONSE (20 Hz to 20 MHz)*	INTEGRATED RESPONSE (4 Hz to 10 MHz)
$\dot{B}$-(FWD UPPER FUSELAGE)	$V_o = -1.816 + 0.1606 \ln \dot{H}$ for $\dot{H} > 2.202 \times 10^5$ A/m·s $V_o = 7.257 \times 10^{-7}\, \dot{H}$ for $\dot{H} < 2.202 \times 10^5$ A/m·s	$V_o = 0.359 \cdot H$
$\dot{D}$-(LEFT WING ONLY)	$V_o = -3.833 + 0.106 \ln \dot{E}$ for $\dot{E} > 6.2 \times 10^{10}$ V/m·s $V_o = 2.555 \times 10^{-12} \cdot \dot{E}$ for $\dot{E} < 6.2 \times 10^{10}$ V/m·s	$V_o = 7.813 \times 10^{-6} \cdot E$
$\dot{D}$-(FUSELAGE)	$V_o = -3.093 + 0.1606 \ln \dot{E}$ for $\dot{E} > 6.26 \times 10^8$ V/m·s $V_o = 2.555 \times 10^{-10} \cdot \dot{E}$ for $\dot{E} < 6.26 \times 10^8$ V/m·s	$V_o = 7.813 \times 10^{-4} \cdot E$
$\dot{J}$-(ALL)	$V_o = -1.26 + 0.0895 \ln \dot{J}$ for 1600 Hz to 20 MHz	None

*Frequency response unless otherwise noted.

SECTION V
TEST RESULTS

The proposed comparison of the shock-excitation and current pulse test techniques could not be conducted due to the proximity of the current return wires to the aircraft and the sensitivity levels of the data channels for the fuselage sensors. Over two days were spent in trying to adjust the test setup so that useful comparative data could be obtained. Dielectric insulators were used in an attempt to prevent the aircraft-to-return conductor arcing. However, the arc location just moved from one high-field location to another as insulation was inserted between the return wires and the aircraft. In addition, the output voltage and current levels were reduced until the generator could no longer be triggered reliably; however, all the fuselage sensors were still saturated.

Since the proposed test data could not be gathered, other representative system tests were conducted on the aircraft. Some interior wire data were gathered for a few current pulse and small output arc (2 1/2 inch) cases using only the MCAIR fiber optic system and bypassing the airborne system completely. Then the skin current distribution around the fuselage was mapped. Finally, some induced voltage measurements were made using the radiated test setup from both the side and the tail of the aircraft. Some sensor data were also gathered during the radiated cases; however, only the frequency content is included in this report as the input radiated fields can not be well-characterized.

5.1 Skin Current Measurements

Skin current vectors were measured at five fuselage locations on the left side of the WC-130 at a distance of 29 feet from the radome. (The propeller blades are located in this measurement plane.) Each location was tested using two $\dot{J}$ sensors (EG&G MGL-S7) which were mounted so that they sampled two orthogonal components of the skin current vector. The measured responses were then integrated, and the resultant vector magnitude and direction were calculated.

The fuselage diameter at this location is approximately 4.5 meters, so that the current is spread over a circumference of about 12.5 meters. The applied total current for these tests was 4.5 KA. Thus, a simple, uniform distribution of the current would produce a current density of approximately 360 A/m. The measured values are presented in Table V-1. The average of the five test values is 342 A/m and agrees well with the uniform value. Individual values vary about the mean by as much as 27 percent. These variations were directly related to the presence of return conductor wires near the measurement locations. Higher current densities were measured where the return conductor wires were close to the test location and lower densities were measured where the return wires were further away. This bunching of current on the fuselage is due to the current flow taking the path that minimizes the overall system inductance.

The direction of the current flow is generally down the length of the fuselage except for the measurement on the bottom of the fuselage. The interaction of the current flow along the bottom of the fuselage with the nearby earth ground is significant and causes substantial azimuthal currents.

5.2 Wire Data

Induced voltage measurements were made on the fuselage and wing wires using the MCAIR fiber optic system either directly across the wire pair itself or after the wire pair response had been fed through the appropriate on-board data channels (like they were measured in flight). The wing wire pair was open-circuited at the wing tip for all tests; whereas the fuselage wire pair's termination was varied to be either open or shorted.

Table V-2 is a summary of the induced voltage responses for the various test conditions. Both the peak transient magnitude and the principal frequency components are given for each case.

In the initial hard-wire tests using the on-board data channels in the measurement scheme, the induced voltage on the fuselage wire was found to be saturating a 10X amplifier in the on-board equipment. No such saturation was found on the wing wire measurement (see Figure V-1). Further measurements, with the on-board channels not in the circuit, showed nearly equal magnitude responses for the two wire circuits, as shown in Figure V-2. These tests indicate that there was a 10X amplifier in the on-board fuselage wire data channel but no such amplification in the on-board wing wire data channel. Thus, to obtain the induced voltage levels (presented in Table V-2) the measured level was divided

TABLE V-1. SKIN CURRENT DENSITY DISTRIBUTION

LOCATION	COMPONENT	PEAK CURRENT (A/m)	RESULTANT VECTOR (MAGNITUDE A/m/DIRECTION*)
TOP	LONGITUDINAL AZIMUTHAL	+380 - 70	386/10°
UPPER 45°	LONGITUDINAL AZIMUTHAL	+330 - 20	331/4°
SIDE	LONGITUDINAL AZIMUTHAL	+430 - 20	430/3°
LOWER 45°	LONGITUDINAL AZIMUTHAL	+250 0	250/0°
BOTTOM	LONGITUDINAL AZIMUTHAL	+250 +200	320/39°

*Parallel to the fuselage axis is 0°.

TABLE V-2. INDUCED VOLTAGE MAGNITUDE AND FREQUENCY SUMMARY

MEASUREMENT TYPE	INDUCED VOLTAGE (V) [FREQUENCIES (MHz)]		
	DIRECT ATTACHMENT TESTS	RADIATED TESTS FROM THE SIDE	RADIATED TESTS FROM THE TAIL
<u>WING WIRE PAIR</u>			
DIRECT - OPEN [2]	4.6 V [1.7 MHz, 4 MHz] [1]	.25 [3.8, 6.6, 2]	.13 [4, 18.5]
CONSOLE - OPEN [3]	4.1 [2, 4]	.32 [4, 8.7, 18]	.31 [4, 1.9]
ONE SIDE GROUNDED [4]	2.4 [4, .6]	.25 [4, 5, 1.5]	.11 [.5, 4, 9]
<u>FUSELAGE WIRE PAIR</u>			
DIRECT - SHORT	4.2 [1.8, 13.8]	.014 [11, 18.5, 10]	.044 [11, 10, 20]
DIRECT - OPEN	2.9 [3.9, 1.8]	.027 [4, 20]	.035 [19.5, 3.8, 11]
CONSOLE - SHORT [5]		.036 [4, 11]	.040 [4, 1.5, 9]
CONSOLE - OPEN [5]		.026 [2.3, 4]	.042 [2.3, 4]
ONE SIDE GROUNDED		.065 [4, 5]	.053 [4, 9]

1 <u>DATA FORMAT</u> - X[Y, Z]; X = induced voltage (V),
Y = primary frequency (MHz),
Z = secondary frequency (MHz)

2 Direct = measurement directly with MCAIR F/O

3 Console = measurement after AF data channel with MCAIR F/O

4 One side grounded = measurement directly with MCAIR F/O

5 Measured values were divided by ten to eliminate data channel amplification.

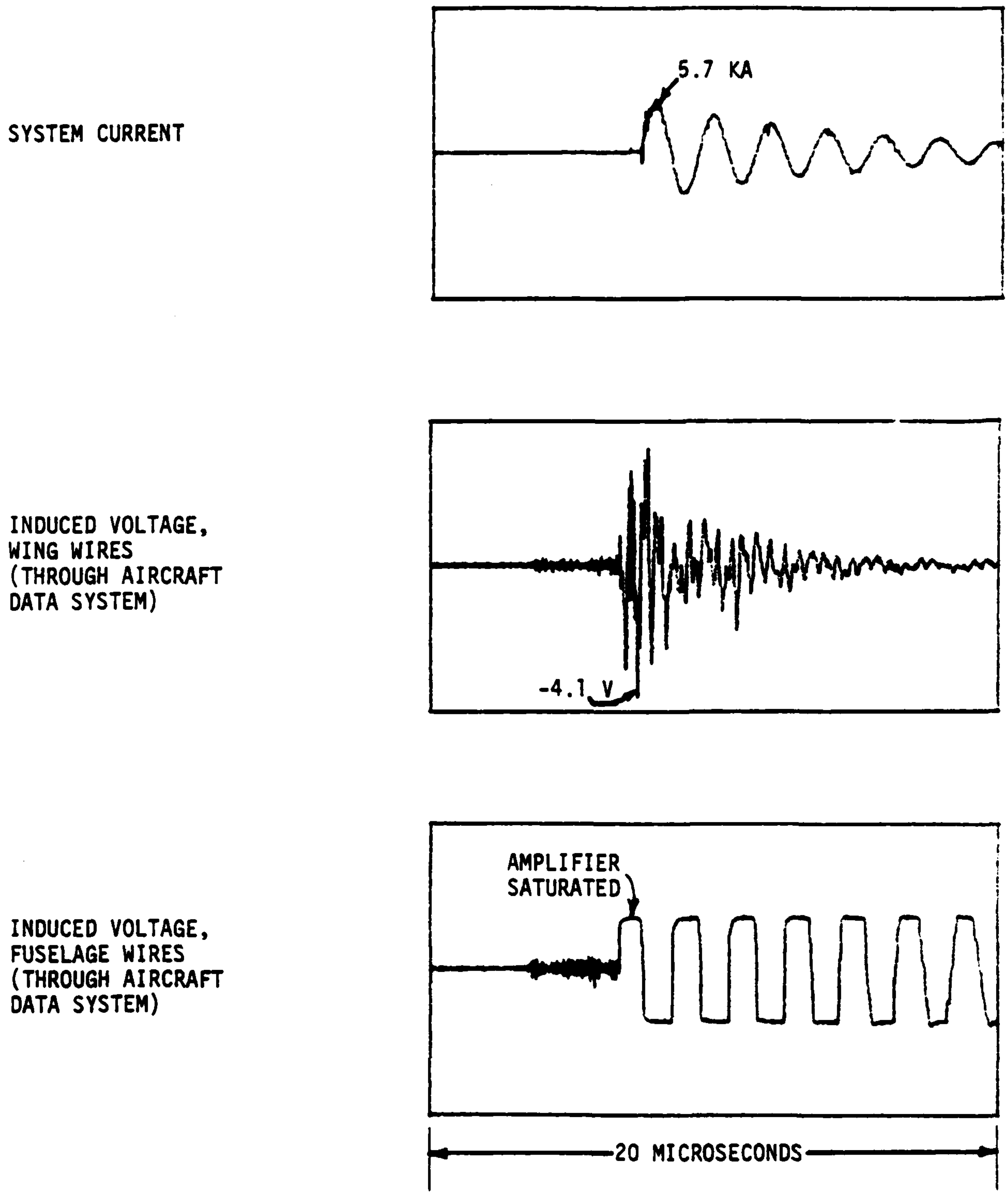

FIGURE V-1. WIRE DATA, CURRENT PULSE TEST
(HARD-WIRED SYSTEM OUTPUT)

SYSTEM CURRENT

INDUCED VOLTAGE,
WING WIRES
(MCAIR F/O SYSTEM ONLY,
DIFFERENTIAL INPUT)

INDUCED VOLTAGE,
FUSELAGE WIRES
(MCAIR F/O SYSTEM ONLY,
DIFFERENTIAL INPUT)

(SHORT CIRCUIT OUTPUT)

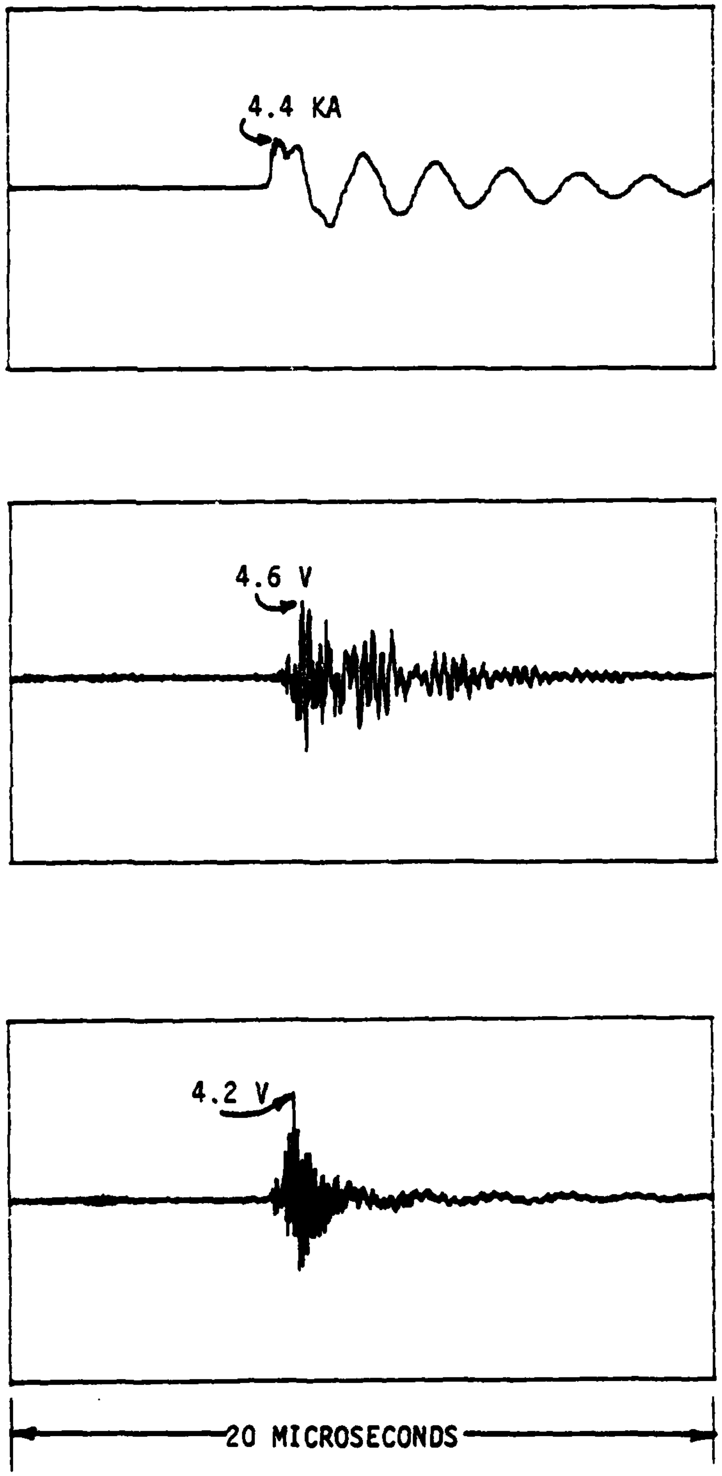

FIGURE V-2. WIRE DATA, 2 1/2-INCH OUTPUT ARC by the factor of ten for the fuselage wire through the on-board channel case. The voltage values for the other cases are presented as measured (Table V-2).

The induced voltage levels for the radiated tests were approximately 100 times smaller than those of the direct current drive tests. The values measured with or without the on-board data channels in the circuits generally agree. In addition, the termination of the fuselage wire has very little effect on the induced voltage level. Representative test shots for the radiated test setups are shown in Figures V-3 through V-7.

5.3 Frequency Data

Figure V-8 is a summary of the frequency data from the interior wires and the aircraft sensors for both the direct attachment and the radiated test cases. Only peaks that have a magnitude greater than 50 percent of the dominant frequency are plotted. The primary frequency content is centered about the 3.5- to 4.0-MHz band. Two sources of this frequency can be postulated. The first source is the aircraft wing whose length is 132 feet. The wing tips are open-circuited in both test configurations, and, therefore, the wing length would act as a half-wavelength transmission line and resonate at ≈3.8 MHz. The second source is the wing wire which is open-circuited at the wing tip and is terminated in a 50-ohm impedance at the measurement end. If the 50-ohm termination is lower than the characteristic impedance of the wing wire pair, then the interior line has an effective low impedance termination at one end and an open at the other. The 66-foot-long line will then resonate as a quarter-wavelength line at approximately 4 MHz also.

Figure V-9 is an average of six fast Fourier transforms (FFT) of induced voltage traces for direct attachment tests. The 0.5-MHz peak is due to the RLC resonance of the entire generator/aircraft circuit. The 2-MHz peak is the quarter-wavelength fuselage resonance. The 3.6-MHz resonance is due to both the wing and the interior wing wire resonances.

ELECTRIC FIELD
(NEAR LEFT WING TIP)

INDUCED VOLTAGE,
WING WIRES
(THROUGH AIRCRAFT
DATA SYSTEM)

INDUCED VOLTAGE,
FUSELAGE WIRES
(THROUGH AIRCRAFT
DATA SYSTEM)

(OPEN CIRCUIT OUTPUT)

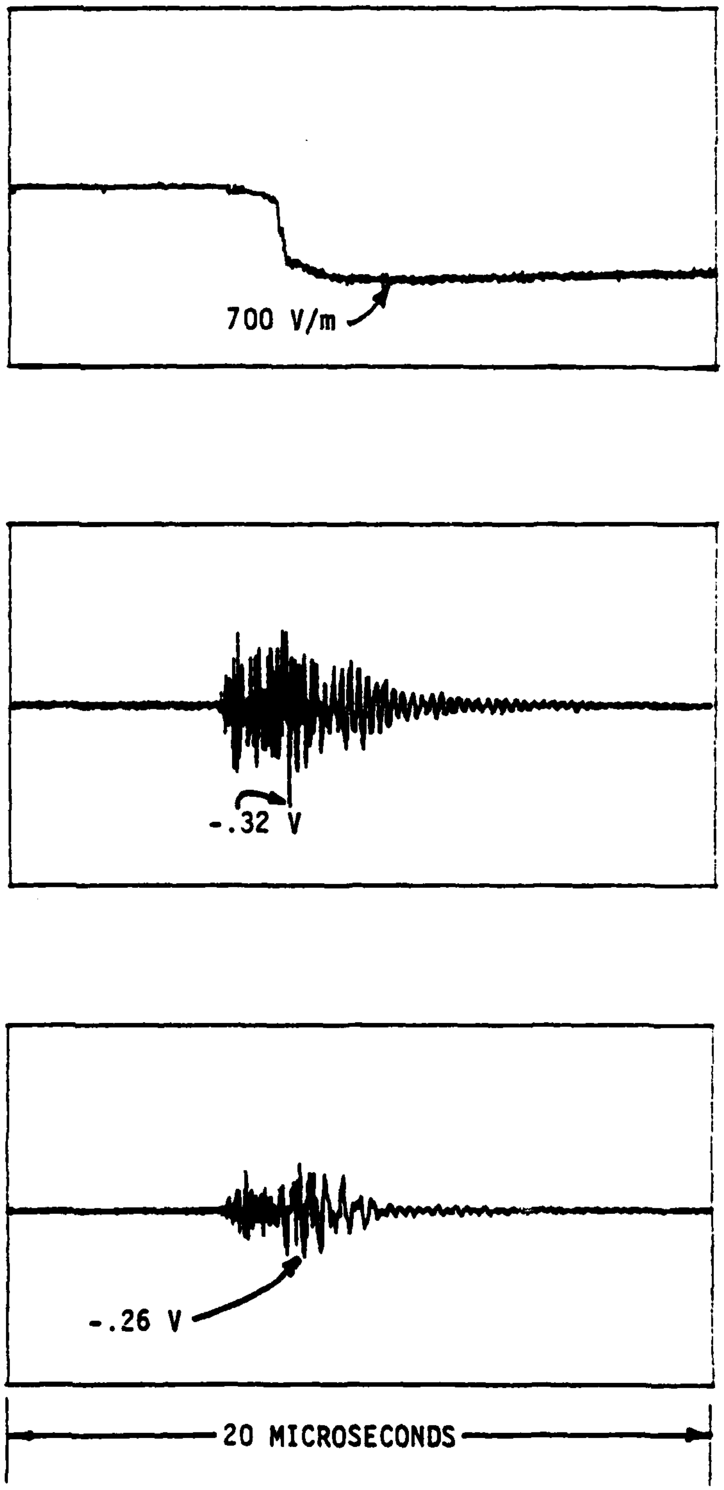

FIGURE V-3. WIRE DATA, PULSE PARALLEL TO THE FUSELAGE, THROUGH AIRCRAFT DATA SYSTEM

ELECTRIC FIELD
(NEAR LEFT WING TIP)

INDUCED VOLTAGE,
WING WIRES
(MCAIR F/O SYSTEM ONLY,
DIFFERENTIAL INPUT)

INDUCED VOLTAGE,
FUSELAGE WIRES
(MCAIR F/O SYSTEM ONLY,
DIFFERENTIAL INPUT)

(OPEN CIRCUIT OUTPUT)

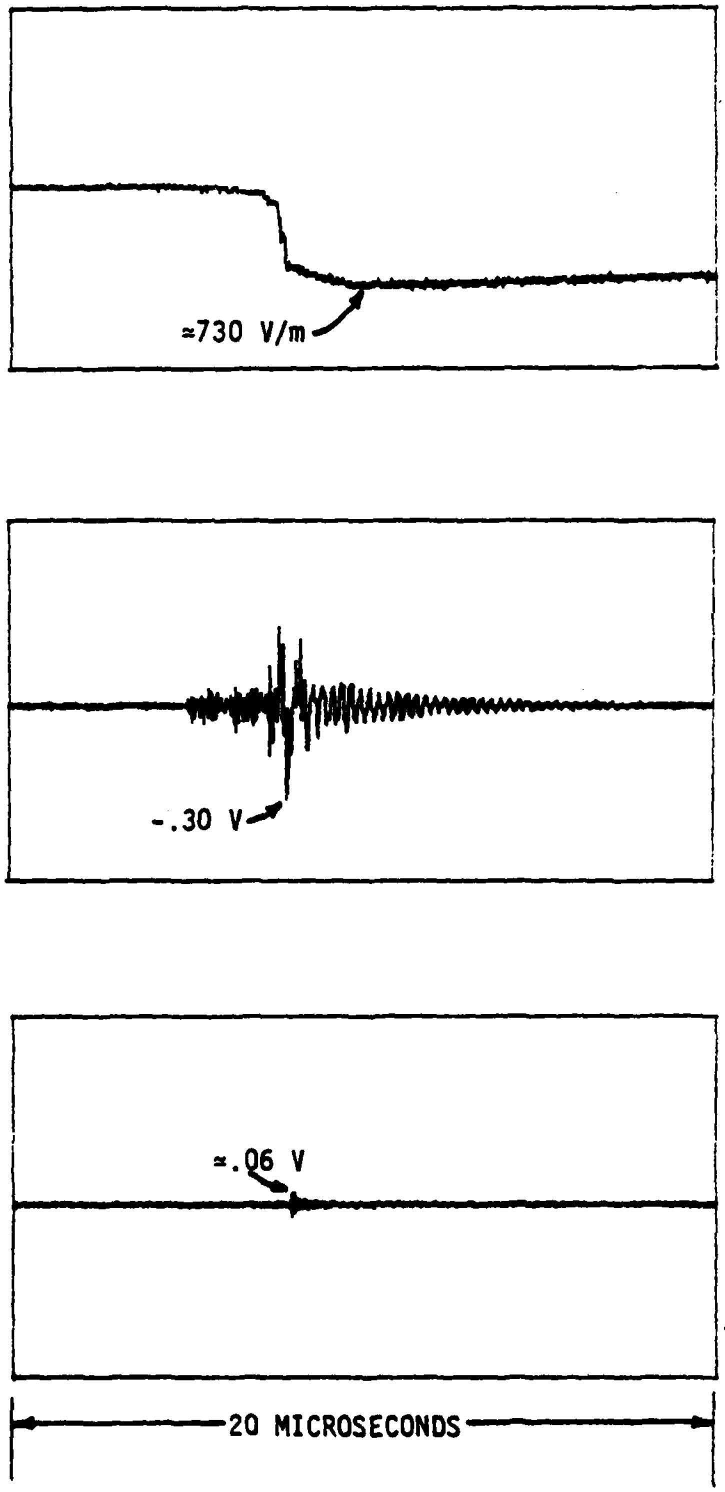

FIGURE V-4. WIRE DATA, RADIATED PULSE PARALLEL TO THE FUSELAGE, MCAIR F/O SYSTEM ONLY

ELECTRIC FIELD
(NEAR LEFT WING TIP)

INDUCED VOLTAGE,
WING WIRES
(MCAIR F/O SYSTEM ONLY,
WIRE "A" GROUNDED)

INDUCED VOLTAGE,
FUSELAGE WIRES
(MCAIR F/O SYSTEM ONLY,
WIRE "A" GROUNDED)

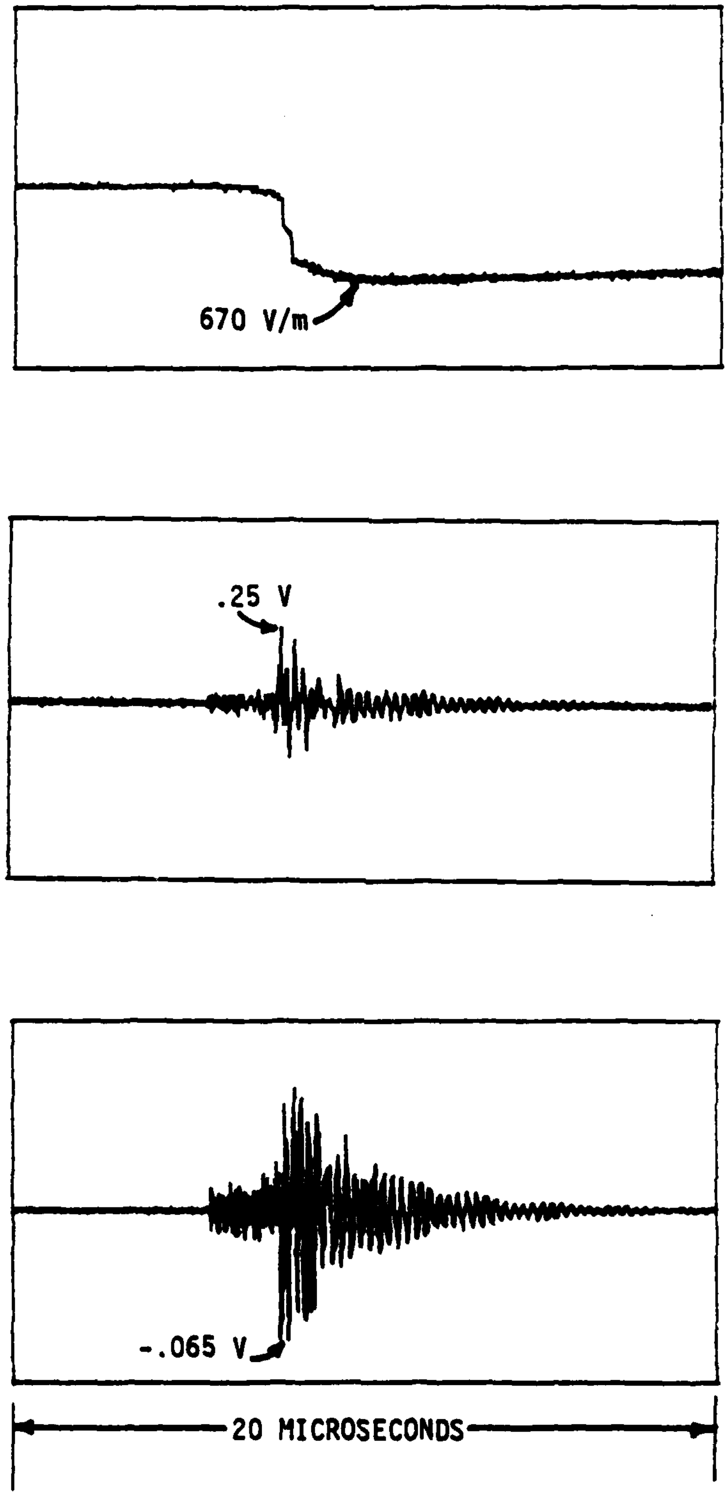

FIGURE V-5. WIRE DATA; RADIATED PULSE PARALLEL TO THE FUSELAGE; ONE SIDE OF THE INTERIOR WIRES GROUNDED

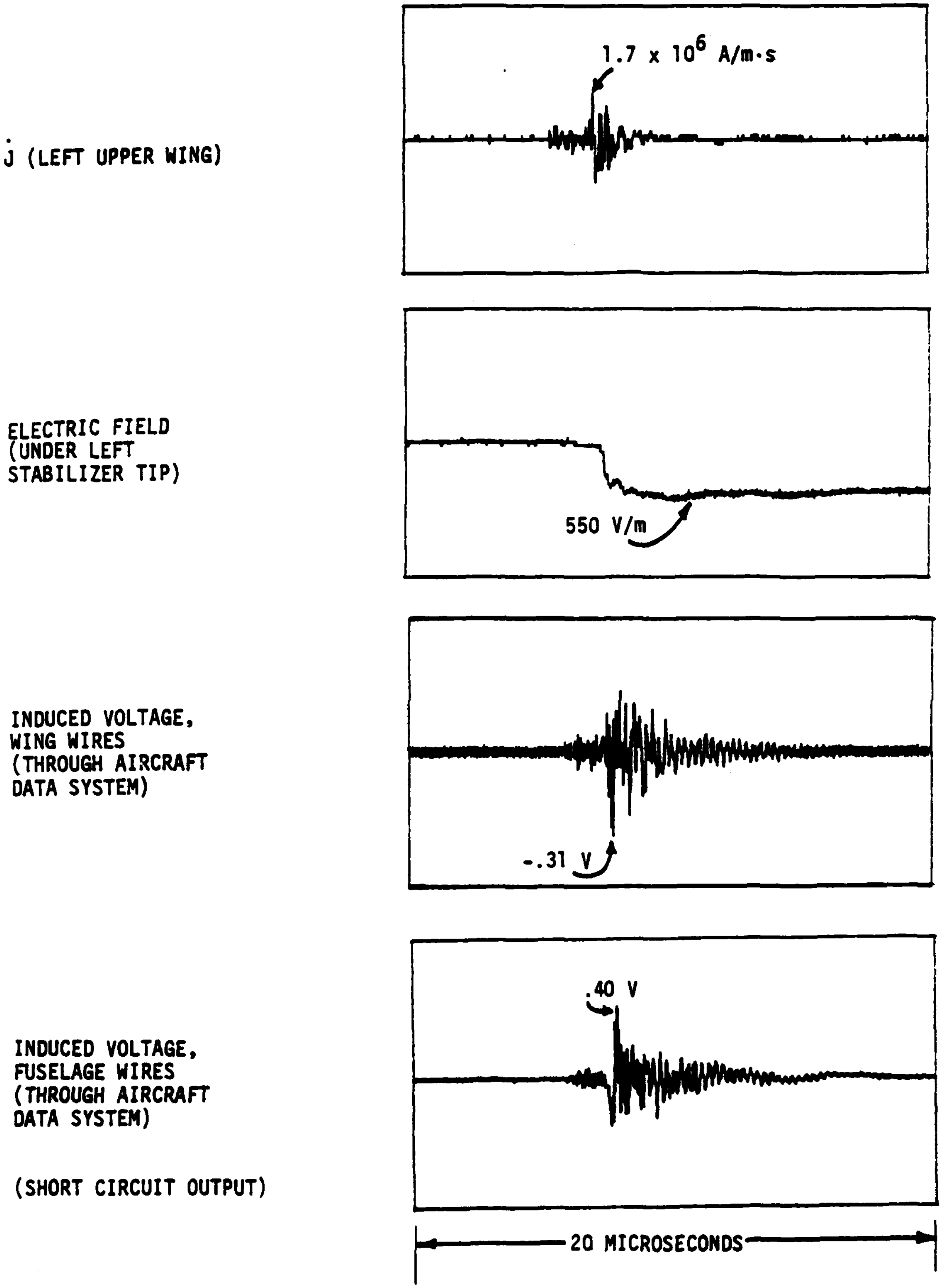

FIGURE V-6. WIRE DATA, RADIATED PULSE FROM TAIL, THROUGH AIRCRAFT DATA SYSTEM

$\dot{H}$ (WING TO WING)
(UPPER FORWARD FUSELAGE)

ELECTRIC FIELD
(UNDER LEFT
STABILIZER TIP)

INDUCED VOLTAGE,
WING WIRES
(MCAIR F/O SYSTEM ONLY,
DIFFERENTIAL INPUT)

INDUCED VOLTAGE,
FUSELAGE WIRES
(MCAIR F/O SYSTEM ONLY,
DIFFERENTIAL INPUT)

(SHORT CIRCUIT OUTPUT)

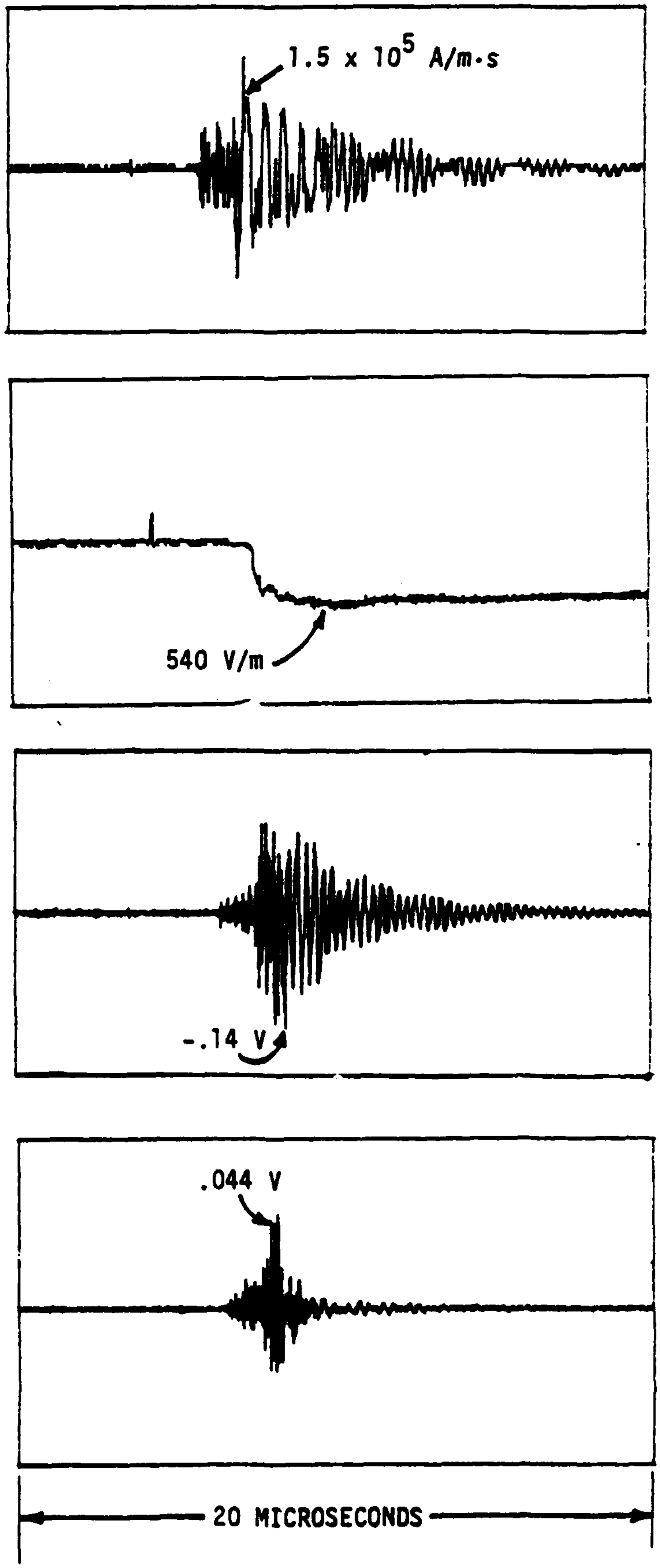

FIGURE V-7. WIRE DATA, RADIATED PULSE FROM TAIL, MCAIR F/O SYSTEM ONLY

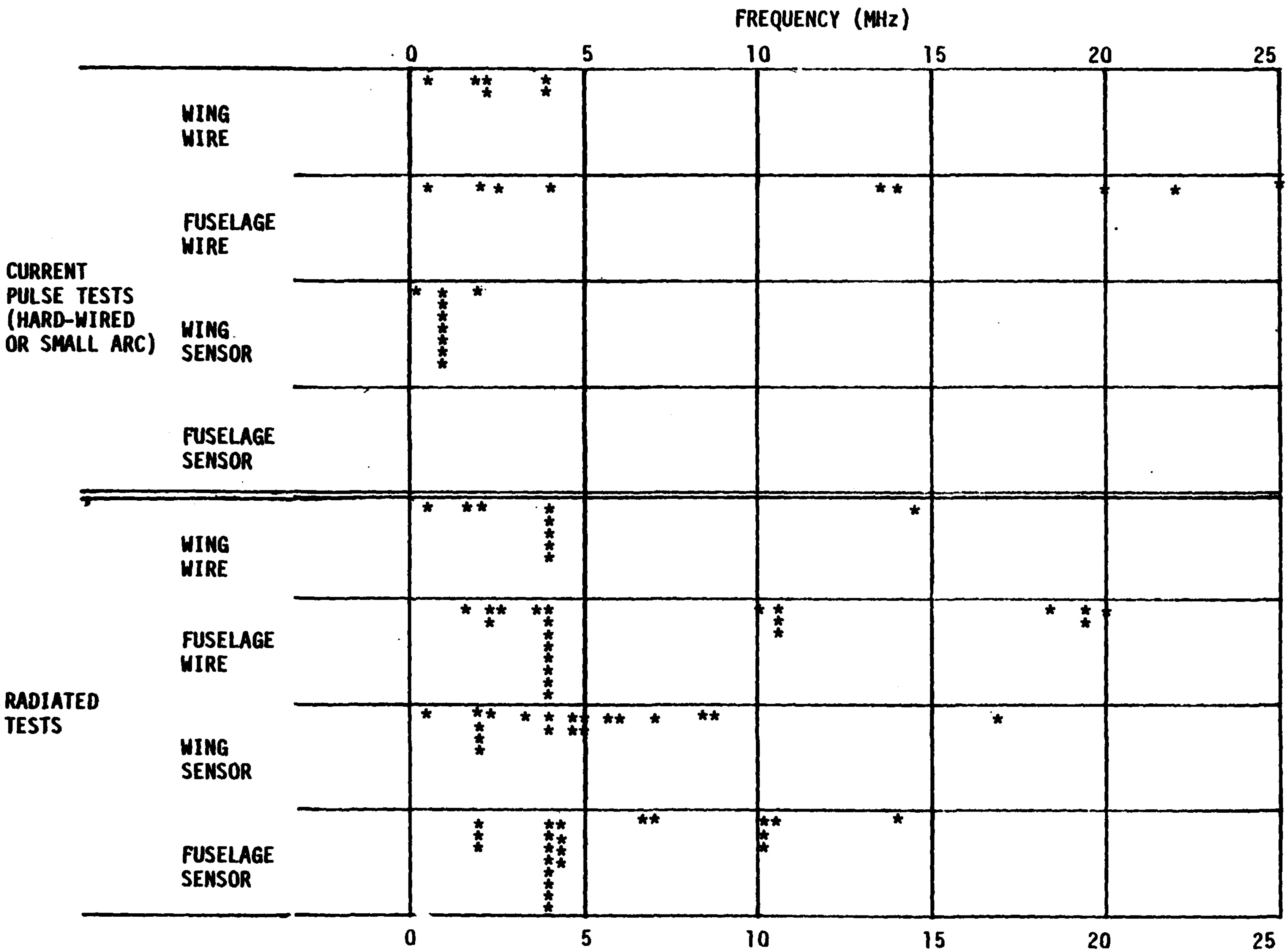

FIGURE V-8. FREQUENCY SUMMARY

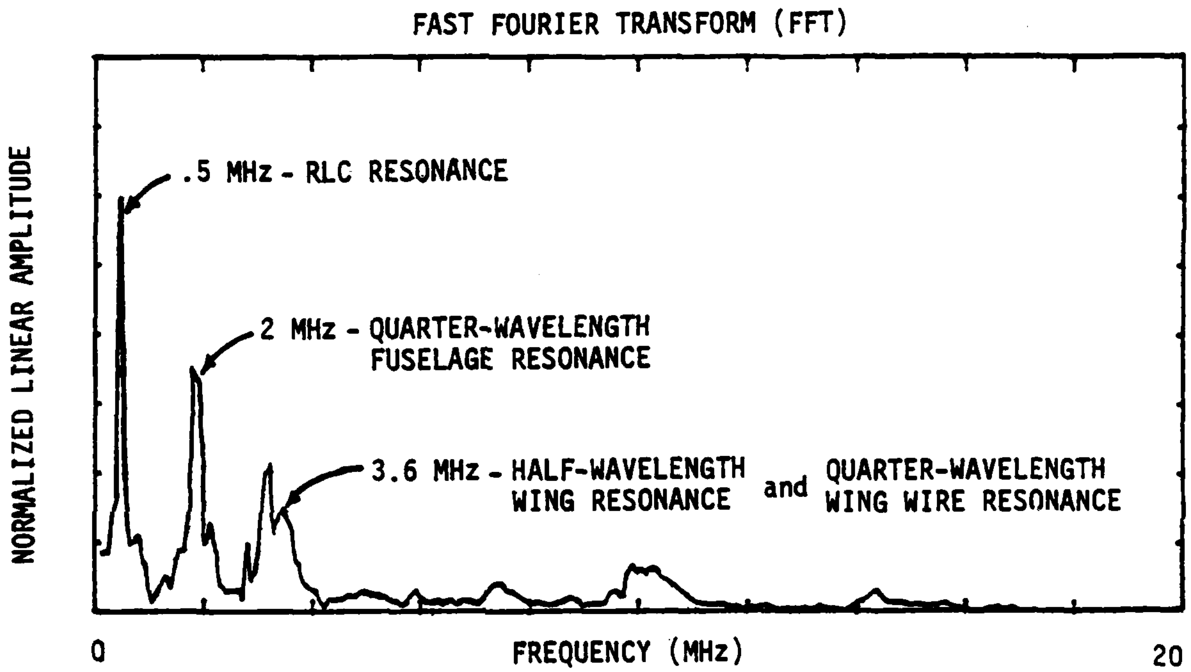

FIGURE V-9. FFT AVERAGE OF SIX INDUCED VOLTAGE TRACES FOR CURRENT PULSE TYPE TESTS

SECTION VI
CONCLUSION

The lightning tests of the WC-130 research aircraft demonstrate that an airborne data system can be tested using both direct attachment and radiated lightning test techniques. The proximity of the current returns and the sensitivity ranges of the aircraft sensors prevented the comparison of the current pulse and shock-excitation test techniques. Only limited induced voltage data was obtained in the direct attachment tests by using a MCAIR fiber optic data link connected directly across the circuit termination.

The purely radiated test technique excited the isolated aircraft in its natural free-body resonances without the added complications of any external connections or the presence of nearby return conductors. Since the abrupt radiated stimulus was not well-characterized, only the frequency data has quantitative significance. The dominant system resonance is approximately 4 MHz and is probably due to the half-wave resonance of the aircraft's wing length. The induced voltage levels for the radiated tests were approximately 100 times smaller than the direct attachment values.

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[1] R. B. Baum, "Airborne Lightning Characterization," Lightning Technology, NASA Conference Publication 2128, FAA-RD-30, April 1980.

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[3] W. G. Butters, J. E. Lenz and K. P. Murphy, "Final Report OV101 Orbiter Lightning Test," McDonnell Douglas Corporation Report MDC A6547, August 1980.

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*USGPO: 1983-659-062-878